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This final report summarizes Yale High Temperature Chemical Reaction Engineering Laboratory research methods/results (Grant AFOSR 84-0034) for the ca. five-year period ending 12/31/88. Our techniques and results are outlined in the areas of (1) laser-based real-time optical techniques for measuring soot particle thermophoretic diffusivities in combustion gases, (2) role of thermophoresis and photophoresis in the capture of soot particles, (3) boundary layer computational methods and correlations for vapor and small particle transport, including the effects of particle size "polydispersity", high mass loading and dopant redistribution, and (4) use of microwave-induced plasma emission spectroscopic (MIPES) methods to follow boron surface gasification kinetics in gaseous streams containing OBOBO(g). Presentations and archive publications describing these techniques and findings are documented, along with examples of impact of our results on research programs elsewhere.

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to

U.S. AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Bolling Air Force Base
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TRANSPORT PHENOMENA AND INTERFACIAL KINETICS IN MULTIPHASE COMBUSTION SYSTEMS

Period Covered: 1 December 1983 - 31 December 1988

Principal Investigator: Daniel E. Rosner

High Temperature Chemical Reaction Engineering Laboratory
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P.O. Box 2159 YS; New Haven, CT 06520

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TRANSPORT PHENOMENA AND INTERFACIAL KINETICS IN MULTIPHASE COMBUSTION SYSTEMS

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Table of Contents

1. INTRODUCTION

The performance of ramjets burning slurry fuels (leading to condensed oxide aerosols and liquid film deposits), gas turbine engines in dusty atmospheres, or when using fuels from non-traditional sources (*e.g.*, shale-, or coal-derived), depends upon the formation and transport of small particles across non-isothermal combustion gas boundary layers (BLs). Even airbreathing engines burning "clean" hydrocarbon fuels can experience *soot* formation/deposition problems (*e.g.*, combustor liner burnout, accelerated turbine blade erosion and "hot" corrosion). Moreover, particle formation and transport are important in many chemical reactors used to synthesize or process aerospace materials (turbine blade coatings, optical waveguides, crucibles, ...). Accordingly, our research is directed toward providing chemical propulsion systems engineers and materials-oriented engineers with new techniques and quantitative information on important particle- and vapor-mass transport mechanisms and rates.

The purpose of this report is to summarize our research methods and accomplishments under AFOSR Grant 84-0034 (Technical Monitor: J.M. Tishkoff) during the *ca.* five-year period 12/1/83-12/31/88. Readers interested in greater detail than contained in Section 2 are advised to consult the published papers cited in Sections 2, 5. Copies of any of these published papers can be obtained by writing to the P.I.: Professor Daniel E. Rosner, at the Department of Chemical Engineering, Yale University, Box 2159 Yale Station, New Haven, CT 06520-2159Y.S., U.S.A. Comments on, or examples of, applications of our research will be especially welcome (see Section 3.3).

An interactive experimental/theoretical approach has been used to gain understanding of performance-limiting chemical-, and mass/energy transfer-phenomena at or near interfaces. This includes the development and exploitation of seeded laboratory flat flame burners (Section 2.1), flow-reactors (Section 2.3), and new optical diagnostic/spectroscopic techniques. Resulting experimental rate data, together with the predictions of asymptotic theories, were then used as the basis for proposing and verifying simple viewpoints and effective engineering correlations for future design/optimization studies.

2. RESEARCH ACCOMPLISHMENTS

Most of the results obtained under Grant AFOSR 84-0034 can be divided into the three subsections below:

2.1 SEEDED FLAME EXPERIMENTS ON CONDENSIBLE VAPOR AND SUBMICRON PARTICULATE TRANSPORT RATES

We have developed and exploited seeded-, atmospheric pressure flat-flame burner techniques (Fig. 1) combined with laser optical probing of chemically inert, reflective targets (*e.g.*, Pt ribbons) and diffusion boundary layers to study rates of chemical vapor deposition, submicron particle deposition (see, Fig. 2 and Rosner and Kim, 1984; Eisner and Rosner, 1985) and condensate evaporation (*e.g.*, $B_2O_3(l)$, Seshadri and Rosner, 1984; Na_2SO_4+$K_2SO_4(l)$, Liang and Rosner, 1987) under well-characterized conditions amenable to theoretical investigation (Section 2.2) and systematic physicochemical model development. Our most recent emphasis has been on the development of a $TiCl_4(g)$-seeded low strain-rate counterflow diffusion flame technique (jointly supported by DOE-PETC) for determining the thermophoretic diffusivity, $(\alpha_T D)_p$, of flame-generated submicron $TiO_2(s)$ "soot" particles. Our diffusivity inference is based on the existence of an easily measured thermophoretically-induced particle-free ("dark") zone on either side of the diffusion flame sheet. Earlier we reported (Gomez *et al.*, 1988) that inferred $(\alpha_T D)_p$-values based

on *observed* dark-zone thicknesses and observed (thermocouple) temperature gradients, but *computed* gas velocities, were within 10% of values expected using a Waldmann's kinetic theory approach for spherical particles. By using LDV (radial) velocity measurements on N_2-diluted flames we confirmed these earlier estimates and made preliminary measurements of the dependence of the inferred $(\alpha_T D)_p$ on carrier gas momentum diffusivity (using helium substitution). The ability to reliably measure and ultimately predict thermophoretic diffusivities of flame-generated particles (carbonaceous soot, Al_2O_3, SiO_2, TiO_2, ...) is clearly important to many technologies, including chemical propulsion, materials fabrication, and hot gas "clean-up".

Perhaps the most interesting and important corollary of our studies of particle thermophoresis relate to potential use of this phenomenon to infer local particle concentrations and local gas temperatures. In unseeded but fuel-rich hydrocarbon/oxygen flames we first demonstrated that carbonaceous soot particle transport to immersed thermocouple probes occured according to the now well-understood laws of thermophoresis (Eisner and Rosner, 1985). Thus, straight-line re-plots of thermocouple diameter *vs.* time data were possible and the slopes (m) of these particular plots, proportional to the local soot volume fraction $f_{v,e}$ were indeed consistent with laser light extinction measurements across these same flames. According to the same theory, one can simultaneously determine local *gas* temperatures — a scheme which we call "thermophoretic thermometry". One variant, is sketched in Fig. 3 (κ is $d\ln k_g/d\ln T$, where k_g is the combustion gas thermal conductivity). Ironically, in this scheme the presence of soot is *exploited* to determine T_g, and is not the obstacle which greatly complicates its accurate inference! We plan to return to these (relatively simple and inexpensive) techniques in our future research.

2.2 MULTIPHASE TRANSPORT THEORY

Because of increasing interest in the Soret 'diffusion' of large, highly nonspherical molecules (*e.g.*, polycyclic aromatic soot precursors and large metal-organic vapors used to deposit thin films with useful optical properties) and the thermophoretic transport of nonspherical submicron particles (*e.g.*, long soot aggregates) we have predicted the ***shape***- and orientation-dependence of their thermal diffusion velocities (see, Fig. 4, and Garcia-Ybarra & Rosner, 1989), including the implications of these effects for coagulation rates (Park & Rosner, 1989a). Of course, particle size and shape also affect Brownian diffusivities, and we have developed useful engineering methods for predicting total mass deposition rates from 'coagulation-aged' *distributions* of particles — including 'fractal' agglomerates (see, *e.g.*, Rosner, 1989; and Rosner & Tassopoulos, 1989). Thermophoretic effects in systems highly loaded with spherical particles (as in the manufacturing of optical waveguides) have also been successfully treated, using extensions of laminar boundary theory (see Fig. 5, and Rosner & Park, 1988; Park & Rosner, 1989). This work extends on earlier results/correlations for lightly loaded but thermophoretically influenced convective flow systems (Gokoglu & Rosner, 1984).

The competition between particle *inertia* and particle thermophoresis has been clarified, especially for the case of axisymmetric laminar impingement flows toward overheated (or undercooled) solid surfaces (Park & Rosner, 1989b). This included prediction of the dependence of the "critical" Stokes number (t_p/t_{flow}) for inertial impaction on wall temperature-ratio and particle mass loading. In the presence of appreciable ***radiation*** energy fluxes, photophoretic ("radiometric") effects can also become important for intermediate size ***absorbing*** particles. Castillo *et al.* (1989) have shown that this effect, like inertia, can drive 'illuminated' particles on to an "overheated" surface. For undercooled surfaces we predicted the dependence of mass transfer coefficient on carbonaceous particle radius (in multiples of the gas mean free-path) and the radiation/Fourier (conduction) heat flux ratio. In situations where the radiative fluxes to the wall are comparable to the 'convective' (conductive-) fluxes we found (Castillo *et al.*, 1989) a noticeable (*ca.* 10%) increase in the deposition rates of such particles.

2.3. GASIFICATION KINETICS OF SOLID BORON

Because of the energetic potential of boron as a solid fuel (or fuel additive) and the likely role of *surface* reactions involving the gaseous oxidants $O_2(g)$ and $B_2O_3(g)$ in the processes of fine

boron-particle ignition, combustion and extinction, we developed new flow reactor techniques and obtained measurements of the intrinsic kinetics of the gasification of B(s) at surface temperatures between about 1300K and 2100K (Zvuloni *et al.*, 1989a). Some of the propulsion implications of these measurements can be demonstrated with the help of a diagram (Fig. 6) of (log) particle diameter *vs* (log) chamber pressure, which not only displays the onset of non-continuum behavior but also the locus of expected particle *extinction* due to "passivation" associated with the kinetically-controlled onset of condensed B_2O_3 at the gas/solid interface.

To make rapid-response gas/solid reaction rate measurements over a large temperature range, we improved and exploited a sensitive spectroscopic technique called *microwave-induced plasma exitation* (MIPE) in which characteristic line emissions from atoms in the gaseous product species of a gas/solid reaction are monitored in a low pressure flow reactor (Fig. 7). This is a modified version of our transonic, vacuum flow reactors developed earlier under AFOSR-support for studying important gas reactions with refractory solids (metals [see, eg., Kiels *et al.*, 1984], semi-metals, ceramics). The reaction *product* vapor species are dissociated and photon emission from the resulting boron (or carbon)-atoms is caused by interaction with the products of a microwave discharge plasma before leaving the reactor. The oxidant $B_2O_3(g)$ (hereafter written OBOBO(g)) is generated from an upstream electrically heated folded metal "boat" (vaporization) source. Our results for the inferred reaction probability, ε, over the broad surface temperature range from *ca.* 1300K to 2050K are displayed in Fig. 8. Note that above about 1400K (at the stated reactant pressure level) this gas/solid chemical reaction is remarkably efficient — more so than boron gasification by $O_2(g)$, O(g), $H_2O(g)$ or $CO_2(g)$. This implies that OBOBO(g) is able to efficiently chemisorb over a broad temperature interval, thereby delivering an O-atom to form the expected gaseous product molecules $(BO)_2$ and BO. Also of considerable interest (relevance to extinction and ignition) is the location of the "low temperature break" in the Arrhenius diagram — *i.e.* the surface temperature below which the kinetics reveal oxide-layer 'protective' behavior at the prevailing oxidizer and water vapor partial pressure.

Apart from studying the (surprisingly modest) effects of the simultaneous presence of $H_2O(g)$ on the abovementioned surface reactions (Zvuloni *et al.*, 1989b), we made preliminary mass-loss measurements for the gasification of *pyrolytic graphite* and *boron carbide*, by OBOBO(g) (Zvuloni *et al.*, 1989c). These measurements may have important implications for boron-containing systems in which suspended organic soot, and/or pyrolytic graphite containment walls, are present.

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3. ADMINISTRATIVE INFORMATION: PERSONNEL, PRESENTATIONS, 'COUPLING ACTIVITIES'

3.1 PERSONNEL

Table 3.1 summarizes the main personnel at Yale University who have contributed to this five-year AFOSR-supported research program, along with the subject matter of each investigator's research contribution:

Table 3.1: SUMMARY OF PERSONNEL AND THEIR CONTRIBUTIONS[g]

Name	Status @ Yale	Primary Contributions[g]
Rosner, D.E.	P.I.[a], Prof. ChE	Overall program direction/research
Castillo J.	PDRA,VS[d]	Thermophoretic transport across boundary layers
Eisner, A.D.	PDRA	Soot -particle deposition rate experiments
Fernandez de la Mora J.	Fac. (ME)	BL theory of particle transport
Garcia-Ybarra P.	PDRA, VS[d]	Kinetic theory of nonpherical particle motion
Gomez, A.	Lecturer, PDRA[b]	Experimental determination of $(\alpha_T D)_p$
Halpern, B.	Fac. (ChE)	Chemical and physical energy accommodation
Liang, B.	GRA (87)	Vapor deposition with BL phase change
Mackowski D.	PDRA[b]	Photophoretic transport of soot
Nagarajan, R.	GRA (86)	BL theory of chemical vapor deposition
Ogen, S.	SRP[e]	Soot particle deposition rate experiments
Oner, A	GRA/PDRA (85)	Microwave-induced plama emission spectroscopy for boron gasification reaction
Park, H.M.	GRA (87)	BL theory of particle deposition
Roy, R.	GRA (MA)	Thermodynamics of non-ideal condensate mixtures
Tanoff, M.	GRA	Experimental estimates of $\alpha_T D_p$
Timmins, M.	UGRA[f]	Measurements of thermophoretic properties of soot particles; deposition rates calcs
Quinlivian, G.	SRP	BL theory with vapor nucleation
Zvuloni, R.	GRA[c] (1989)	Boron gasification kinetics

[a] Principal Investigator
[b] PostDoctoral Research Associate
[c] Graduate Research Assistant (year of Ph.D. degree)
[d] Visiting Scholar
[e] Summer Research Program, Yale Engineering and Applied Science
[f] UnderGraduate Research Assistant
[g] see Section 5 (arranged alphabetically by first author) for specific publications

3.2 TALKS AND PRESENTATIONS BASED, IN PART, ON OSR-GRANT-SUPPORTED RESEARCH

Table 3.2 belows lists a total of *55* talks based on this research program over the *ca.* 5 year duration of Grant AFOSR 84-0034. While emphasizing domestic conferences, universities and laboratories in the USA, they include presentations made abroad (England, France, Spain, Italy, Israel, Australia, New Zealand in connection with Prof. Rosner's Fall '85 and '88 leaves from Yale University (to permit full-time research and research-related travel free of teaching responsibilities).

Table 3.2: SUMMARY OF TALKS/PRESENTATIONS[1] BASED ON AFOSR 84-0034

Date	Host Organization	Location
3/3/84	Yale U.	Yale
3/12/84	General Motors Research Labs	Warren, MI
6/6/84	29th Int. Gas Turbine Conf.	Amsterdam, Netherlands
6/19/84	OSR boron combustion workshop	Pittsburgh, PA
6/21/84	OSR/ONR contractors Mtg	Pittsburgh, PA
7/25/84	Gordon Conf.; High Temp.Chem.	Wolfboro, NH
11/30/84	Sandia Labs	Livermore, CA
12/16-21/84	PCH#5 (Levich)	Tel Aviv, Israel
2/18/85	U. Pennsylvania	Philadelphia, PA
8/5/85	ASME/AIChE Heat Transfer Conference	Denver, CO
9/18/85	Cambridge U.	Cambridge, UK
9/27/85	Sheffield U.	Sheffield, UK
10/2/85	CEGB-Marchwood Labs	Southampton, UK
10/16/85	Technion IIT, AeroE	Haifa, Israel
10/23/85	Technion IIT, ChE	Haifa, Israel
11/12/85	ENSIC-CNRS	Nancy, France
11/18/85	Comb./High Temp. Res. Ctr.	CNRS, Orleans, France
11/19-20/85	Amer. Assoc. Aerosol Res.[4]	Albuquerque, NM
11/23/85	City University, AeroE	Madrid, Spain
11/26/85	Polytechnic University	Seville, Spain
11/28/85	U.N.E.D. Fund. Physics	Madrid, Spain
12/4/85	U. Provence-Ctr. Dynamics/Thermodynamics of Fluids	Marseilles, France
12/18/85	U. Bologna	Bologna, Italy
12/19/85	Tech. Univ. Milan, AeroE	Milan, Italy
6/16/86	Stanford U/OSR Contractors Mtg	Palo Alto, CA
6/19/86	Stanford U/OSR Contractors Mtg	Palo Alto, CA
7/10/86	American Sci. (Sigma Xi)	New Haven, CT
7/1-15/86	NATO Summer school on PCH[5]	La Rabida (Huelva) Spain
11/5/86	AIChE Nat. Mtg.	Miami, FL
11/25/86	Princeton U. AeroE/ME/ChE	Princeton, NJ
12/16/86	Comb. Inst. – Eastern States Section[2]	San Juan, Puerto Rico
3/(9-13)/87	Engineering Foundation: Chem. Reaction Engrg	Santa Barbara, CA
6/16/87	Italian-French Comb. Inst.[2]	Amalfi, Italy
7/22/87	NASA-Lewis Lab	Cleveland, OH
7/23/87	Shell Development Co.	Houston, TX
8/11/87	ASME/AIChE	Pittsburgh, PA
9/(15-17)/87	Amer. Assoc. Aerosol Res.[6]	Seattle, WA
9/15/87	AVCO-Lycoming-Textron	Stratford, CT

(continued next page)

Date	Host Organization	Location
10/10/87	Electrochem. Soc. (US, Japan)	Honolulu, Hawaii
11/(2-6)/87	Comb. Inst.[2]	Gaithersburg, MD
11/2/87	ChE Dept., J. Hopkins U.	Baltimore, MD
11/20/87	Amer. Inst. Chem. Engrg.	New York, NY
11/20/87	Amer. Inst. Chem. Engrg.[b]	New York, NY
5/17/88	Electrochemical Soc.	Atlanta (GA)
6/16/88	AFOSR	Pasadena (CA)
8/17/88	Combust. Inst.[2]	Seattle (WA)
8/17/88	Combust. Inst.[3]	Seattle (WA)
10/11/88	Combust. Inst. (Australia/NZ)	Sydney (Australia)
10/13/88	BHP-Central Res. Lab.	Newcastle (Australia)
10/27/88	ChE Dept.-U. Sydney	Sydney (Australia)
11/9/88	ME Dept.-U. Sydney	Sydney (Australia)
11/14/88	State Electric Comm.-Victoria	Melbourne (Australia)
11/24/88	ChE Dept.-U. Queensland/State Electric Comm.	Brisbane (Australia)
11/28/88	ChE Dept.-U. Canterbury	Christchurch (N-Zealand)
12/8/88	ChE Dept.-U. Auckland	Auckland (New Zealand)

[1] Presented by Professor Daniel E. Rosner (unless otherwise specified)
[2] Presented by Dr. Alessandro Gomez
[3] Presented by Dr. Pedro Garcia-Ybarra
[4] Presented by Dr. A. Eisner
[5] Presented by Dr. Jose L. Castillo
[6] Presented by Dr. Juan Fernandez de la Mora

3.3 "COUPLING" ACTIVITIES

Our earlier AFOSR studies of surface-catalyzed atom recombination heating and incomplete chemical energy accommodation continue to be used and cited by NASA scientists/research engineers concerned with space shuttle heat transfer measurements (see, eg. Kolodziej P. and Stewart D.A., AIAA Paper 87-1637 (June 1987) and space shuttle material atom recombination coefficient measurements (cf. work of Y.C. Kim and M. Boudart (Stanford U., ChE Dept.) monitored by H. Goldstein and R. Altman at NASA-Ames Research Center. Parallel hypersonic vehicle work in Russia ('Buran' program), Europe ('Hermes' program) and Japan appears to be going on, with periodic citations to our OSR-supported publications.

In the area of two-phase fluid dynamics, a concept (the "effective Stokes number") that we introduced in 1983 to correlate the effects of geometry, Mach number, and particle Reynolds number on inertial impaction is finding widespread use in engineering research — with interesting recent examples (being Wang H.C., *J. Aerosol Sci.* **17** [5], 827-837, 1986; Wessell, R.A. and Righi J., *J. Aerosol Sci. Tech.* **9**, 29-60, 1988; L.J. Forney's recent AIAA paper on impaction on a supersonic wedge; and recent research on fouling in waste heat recovery systems, Glenn and Howarth [Nat. Eng. Lab., Scottland] Inst. Mech. E. [UK] **1**, 401-420, 1988).

Our research on soot particle thermophoresis (*e.g.*, Eisner and Rosner, "Experimental Studies of Soot Particle Thermophoresis in Non-Isothermal Combustion Gases Using Thermocouple Response Techniques", *Combustion and Flame* **61**, 153-166, 1985) has led to advances in soot sampling techniques (from laminar hydrocarbon flames) which are "gentle" and unbiased with respect to particle size (Dobbins, R.A. and Megaritis, C.M., Langmuir [ACS] 3,

254-259, 1987). Moreover, the existence of 'dark zones' (particle-free) near hot surfaces, exploited in our labratory to experimentally determine $\alpha_T D_p$, is of considerable interest to researchers who use LDV and laser sheet light scattering techniques to map flow fields in combustors (*e.g.*, Roquemore, M. *et al.*). This phenomenon also provides the basis of a potentially interesting "thermally driven"* submicron particle separation ("gas cleaning") scheme of interest in several important technologies — including semi-conductor processing (Friedlander, S.K., Fernandez de la Mora, J. and Gokoglu, S.A., *J. Colloid Int. Sci.* **125** [1] pp.351-355, 1988).

Our present research on vapor and particle transport in combustion systems has strongly influenced new programs at NASA Lewis Research Center dealing with the chemical vapor deposition of ceramic 'barrier' coatings for high temperature turbine applications (contact C. Lowell, C.A. Stearns, S.A. Gokoglu). For example, an 'asymptotic' approach (comparing the LTCE and CF-) limits for predicting CVD-rates) we have developed and exploited (Rosner, Nagarajan, Kori and Gokoglu, 1987) has been applied at NASA-Lewis Research Laboratories in the context of alkali-salt deposition in combustion turbines (see, Gokoglu, S.A., *J. ElectroChem. Soc.* **135** [6], 1562-1570, 1988).

Our new kinetic data on the $O_2(g)/B(s)$ and $B_2O_3(g)/B(s)$ reactions above 1400K are of considerable interest to chemical propulsion engineers (*e.g.* M. King, Atlantic Research Corp.) concerned with making realistic predictions of B-particle ignition conditions, combustion rates, and extinction behavior.

Finally, the writer is pleased to report that the textbook/treatise: **Transport Processes in Chemically Reacting Flow Systems** (Butterworths, Stoneham, MA, 1986) is gaining widespread acceptance in U.S. engineering graduate schools and U.S. Government/Corporation Laboratories. This, plus a worldwide demand, has necessitated a second printing (September 1988) and the book won the 1988 Meriam/Wiley Award of the American Society of Engineering Education. It now seems likely that a third printing will be required in 1990. As explicitly noted on page xxvi of the Preface, this book owes much to U.S. Air Force-OSR support of the author's research in the general area of transport phenomena in multiphase chemically reacting systems. For a recent review, see Libby P.A., *AIAA J.* **26** [12] 1528 (1988).

4. CONCLUSIONS

In our OSR-sponsored Yale HTCRE Lab research during this 5-year period, necessarily only briefly described here, we have shown that new methods for rapidly measuring vapor- and particle-mass transfer rates, combined with recent advances in convective mass transfer theories, provide useful means to incorporate important, but often previously neglected, mass transport phenomena in many propulsion engineering and materials engineering design/optimization calculations. We have demonstrated the potentially important effects of new "phoretic" phenomena, high local particle mass loading, 'polydispersed' particle populations, non-negligible particle inertia, and highly nonspherical particles, aggregates (or molecules). To shed light on boron particle ignition, quasi-steady combustion and extinction, we have also studied not only the remarkably efficient $B_2O_3(g)/B(s)$ reaction, but also its $B_2O_3(g)/C(s)$ analog, in the broad temperature interval: 1300K-2100K, both in the absence and presence of $H_2O(g)$. We also supplemented these gasification kinetic studies with preliminary experimental/theoretical studies of the *condensation* kinetics of $B_2O_3(g)$.

While some of this research remains to be extended, the results summarized/documented here (see Section 5) should be of considerable use to the community of combustion/propulsion and materials engineers.

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* inertial effects (exploited, *e.g.*, in cyclones, impactors, ...) are ordinarily ineffective for highly submicron particulate matter

PUBLICATIONS BASED ON AFOSR 84-0034 RESEARCH

Castillo, J.L. and Rosner, D.E., "Equilibrium Theory of Surface Deposition from Particle-Laden Dilute, Saturated Vapor-Containing Laminar Boundary Layer", *Chem. Engrg. Sci.* **44**, [4], 939-956 1989)

Castillo, J.L. and Rosner, D.E., "Theory of Surface Deposition from a Unary Dilute Vapor-Containing Stream Allowing for Condensation within the Laminar Boundary Layer", *Chem. Engrg. Science* **44**, [4], 925-937 (1989)

Castillo, J.L., Mackowski, D.W., and Rosner, D.E., "Photophoretic Contribution to the Transport of Absorbing Particles Across Combustion Gas Boundary Layers", presented at ACS 197*th* Annual Meeting — *Symposium on Ash Deposition*, Dallas, 9-14 April (1989); *Progress in Energy and Combustion Science*, Pergamon Press (to appear).

Eisner, A.D. and Rosner, D.E., "Experimental and Theoretical Studies of Submicron Particle Thermophoresis in Combustion Gases", *J. PhysicoChemical Hydrodynamics* **7**, [2/3], 91-100, (1986)

Eisner, A.D. and Rosner, D.E., "Experimental Studies of Soot Particle Thermophoresis in Non-Isothermal Combustion Gases Using Thermocouple Response Techniques", *Combustion and Flame* **61**, 153-166 (1985)

Fernandez de la Mora, J. and Rosner, D.E., "Boundary Layer Effects on Particle Impaction and Capture", *ASME Trans.-J. Fluids Engrg.* **106**, 113-114 (1984)

Garcia-Ybarra, P., and Rosner, D.E., "Thermophoretic Properties of Small Nonspherical Particles and Large Nonspherical Molecules," *AIChE J.*, **35**, [1], 139-147 (1989).

Gokoglu, S.A. and Rosner, D.E., "Correlation of Thermophoretically-Modified Small Particle Diffusional Deposition Rates in Forced Convection Systems with Variable Properties, Transpiration Cooling and/or Viscous Dissipation", *Int. J. Heat and Mass Transfer* **27**, 639-645 (1984)

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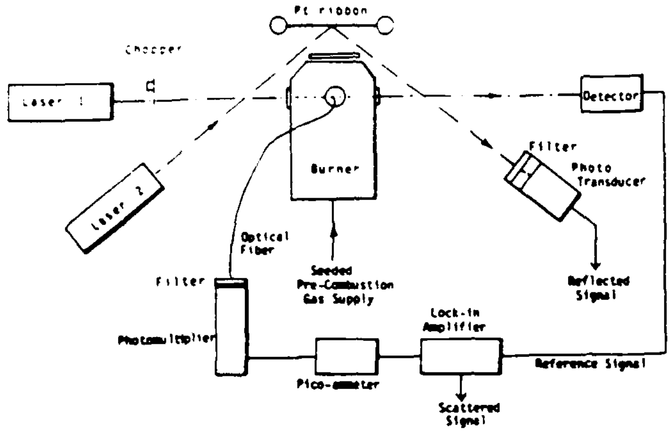


Fig.1 Seeded flat-flame burner and optical techniques for monitoring submicron particle deposition from combustion gases to solid targets (after Rosner & Kim, 1984).

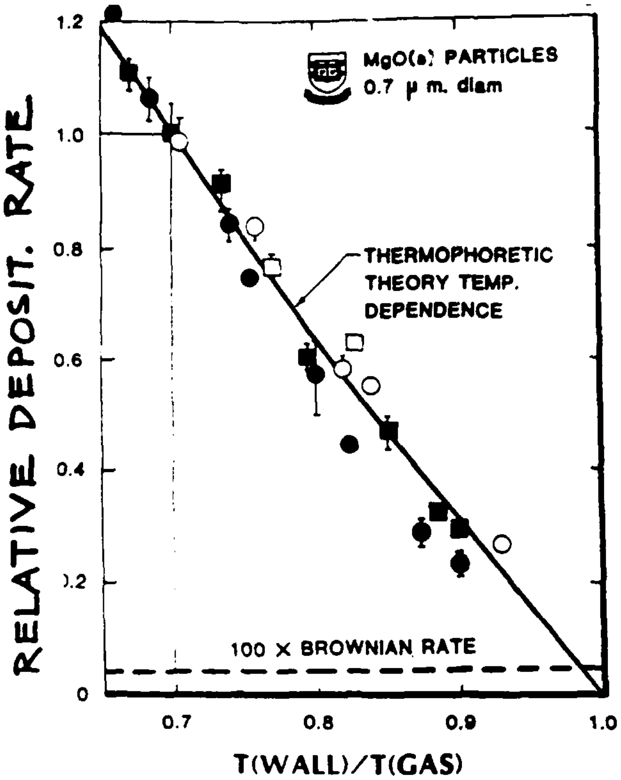


Fig.2 Experimentally observed (Rosner & Kim, 1984), and theoretically predicted (Gokoglu & Rosner, 1984) relative deposition rates of submicron solid particles to cooler solid targets.

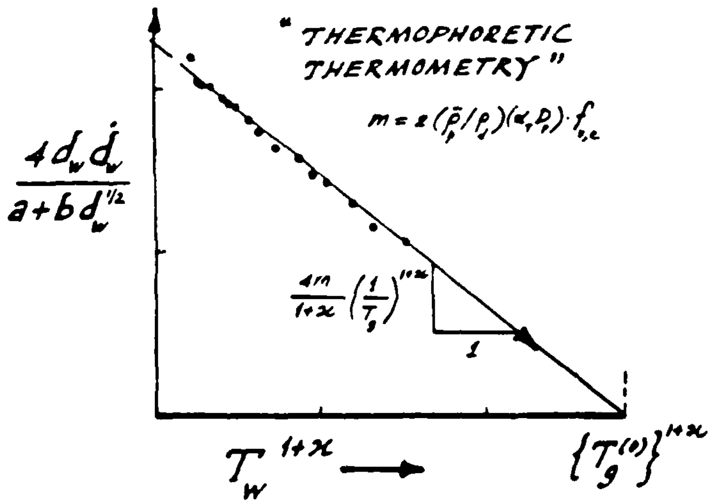


Fig.3 Gas temperature inference based on the response of a thermocouple to the thermophoretic acquisition of soot (after Eisner & Rosner, 1985).

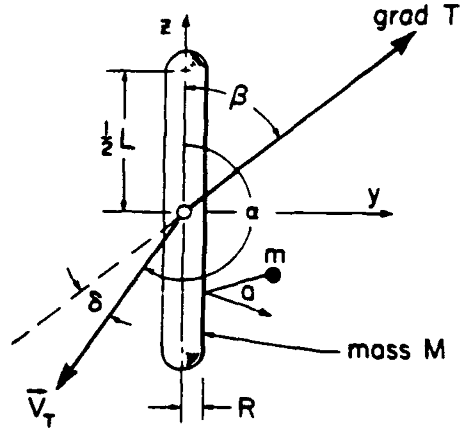


Fig.4 Sphero-cylindrical particle in a non-uniform temperature gas showing the choice of coordinates and notation (after García-Ybarra & Rosner, 1989)

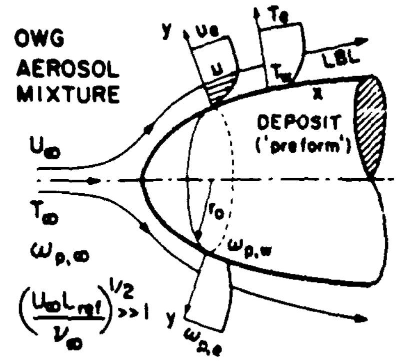


Fig.5 Viscous flow configuration, body-oriented bounary layer coordinate system and nomenclature; axisymmetric case (k=1) shown (after Rosner & Park, 1988).

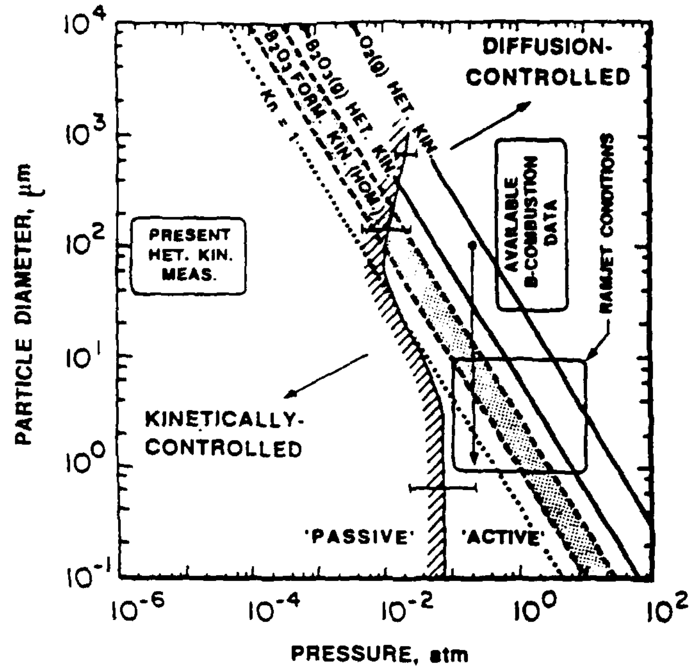


Fig.6 Boron particle combustion 'map' displaying expected: 1) diffusion-controlled or kineticaly-controlled regimes for B_2O_3(g) and O_2(g) reactions with the surface, 2) transition to non-continuum behavior, 3) domains of present and past experimental investigations and principal ramjet interest, and 4) extinction due to surface passivation (after Zvuloni, Gomez & Rosner, 1989).

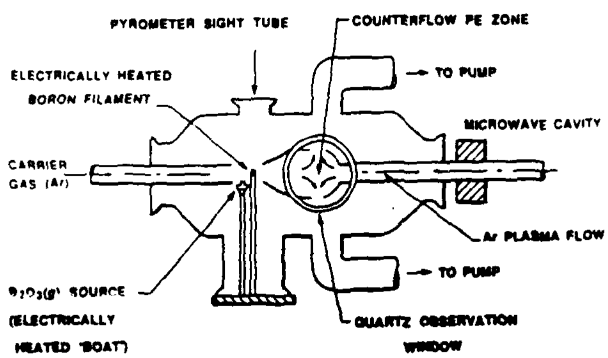


Fig. 7 Flow reactor configuration for kinetic studies of gas/solid reactions using product detection via Microwave Plasma Emission Spectroscopy (MIPES). Configuration shown includes 'boat' source of B_2O_3(g) reactant vapor upstream of transverse boron filament (after Zvuloni, Gomez & Rosner, 1989).

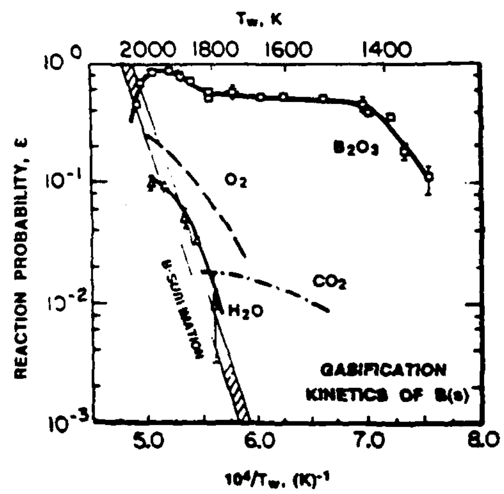
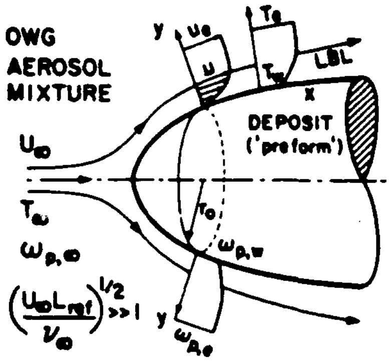


Fig.8 Experimental results (Arrhenius diagram) showing inferred reaction probabilities for gasification kinetics of solid boron by B_2O_3(g), O_2(g), H_2O(g) and CO_2(g) at reactant pressure of the order of 10^{-2}Pa (after Zvuloni, Gomez & Rosner, 1989).



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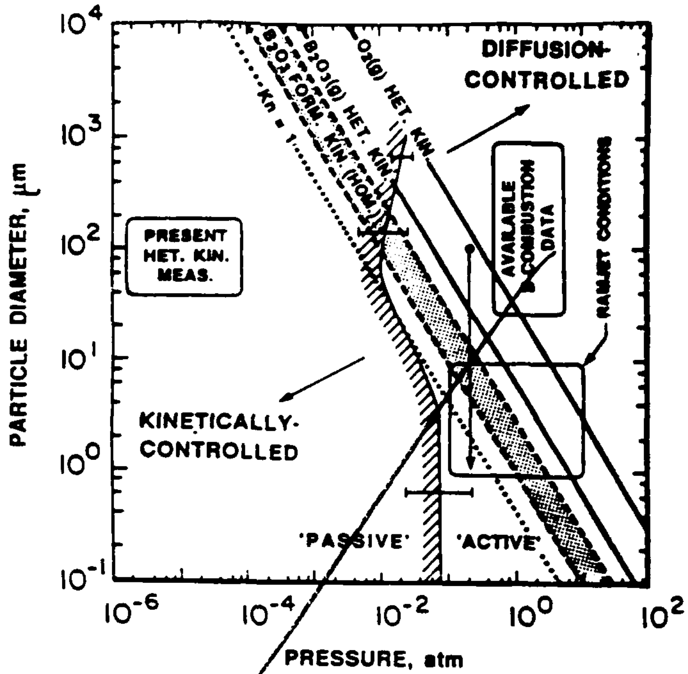

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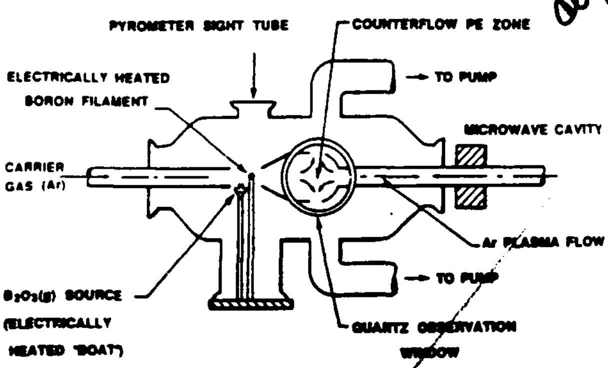

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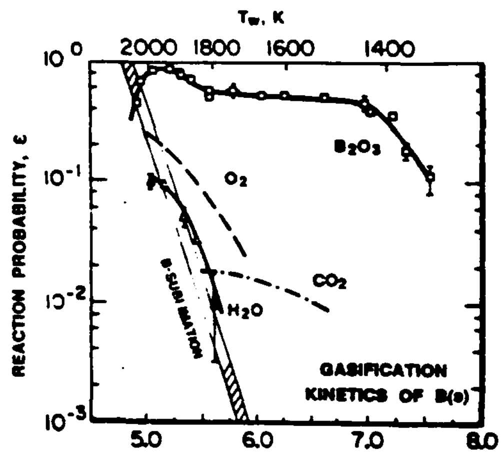

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